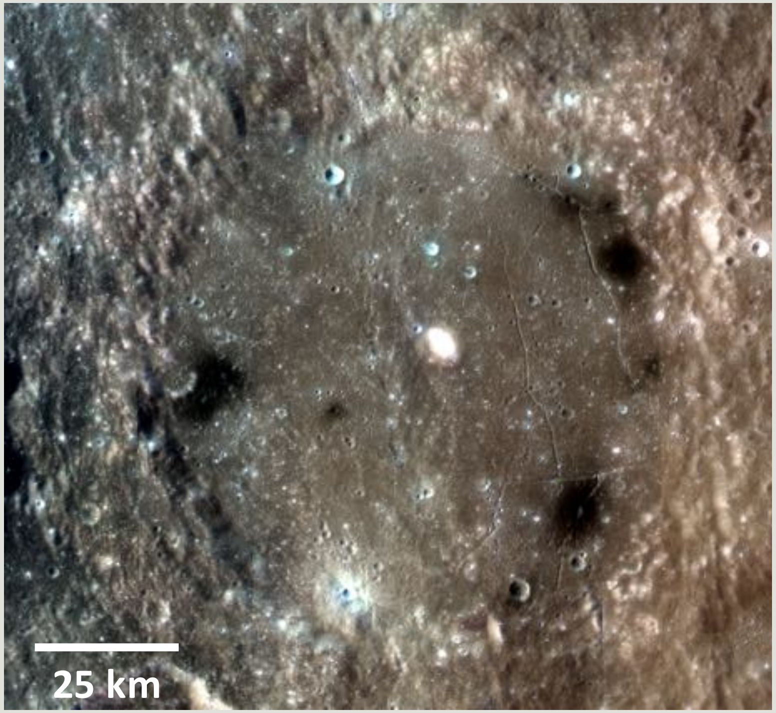


Alphonsus crater with 11 pyroclastic vents

Rationale for Landing Sites at Lunar Pyroclastic Deposits

Lisa Gaddis
USGS Astrogeology Science Center

Jan 11, 2018
Lunar Science for Landed Missions Workshop

Outline

- Overview of the lunar pyroclastic deposits
- Resource potential
- ISRU, Accessibility and Traversability
- Recommendations for lunar landing sites

Lunar Pyroclastic Deposits

USGS

Explosively emplaced volcanic deposits

- Diffuse boundaries, association with vents

Ancient, by association with lunar maria

- Most basalts erupted during the Late Imbrian (3.6 to 3.8 BY ago)
- Hiesinger et al. (2000) crater counts

Globally distributed

- Observed along margins of lunar maria
- Often associated with floor-fractured craters in faulted regions

Range of sizes (~50,000 to 3 km^2):

- Very Large = 50000 – 1000 (22)
- Large = <1000 – 400 (19)
- Medium = <400 – 200 (12)
- Small = <200 – 100 (18)
- Very Small = <100 – 3 (16)

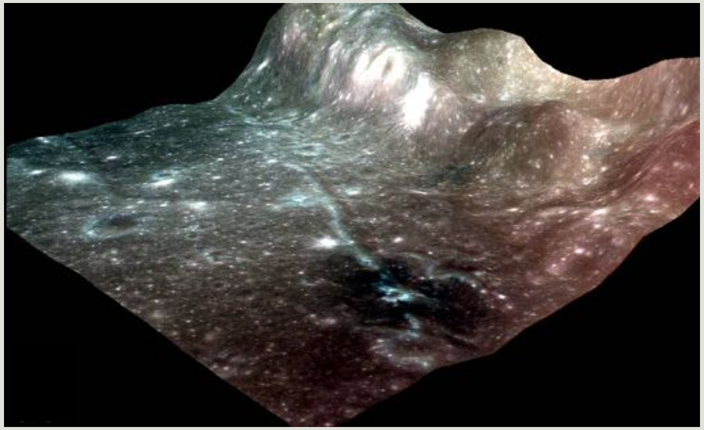
87

Regional

Localized

Gustafson, et al., 2012

Gaddis et al., 2003

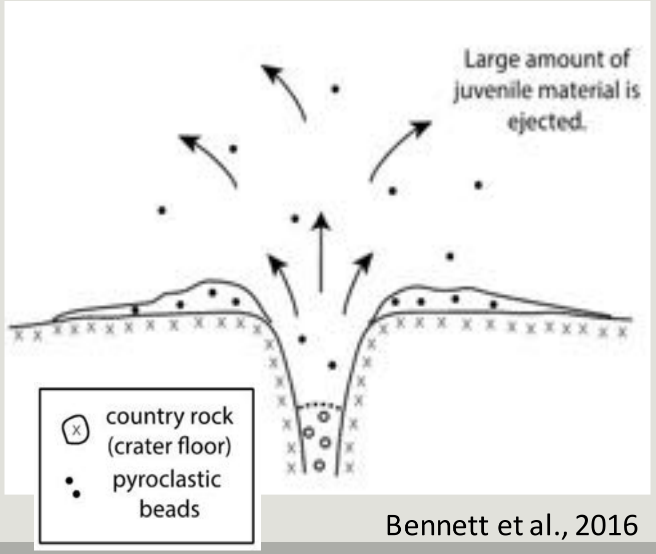


Alphonsus NE floor vents
Kaguya MI color, 20 m/pixel, ~24 km across

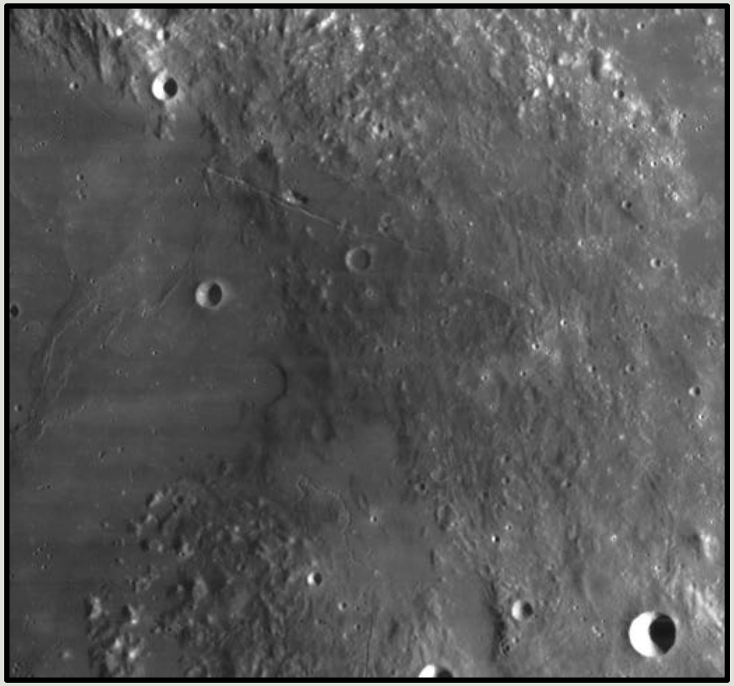
Regional Pyroclastic Deposits

USGS

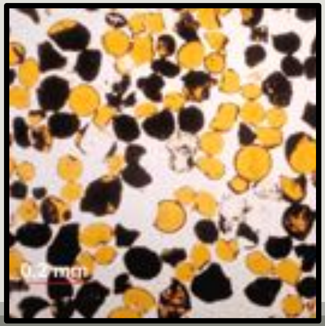
- **Formed by fire-fountaining (Head & Wilson, 2017)**
  - High volatile content (H, H_2O, CO, SO_2), ballistic trajectories
  - Widely distributed, ~thin deposits
  - ***Abundant juvenile material***
    - ***Quenched glass, crystalline beads (often Hi TiO_2)***
- **Type Examples**
  - Taurus Littrow (Apollo 17)
  - ***Rima Bode,*** Sinus Aestuum, Sulpicius Gallus



Bennett et al., 2016



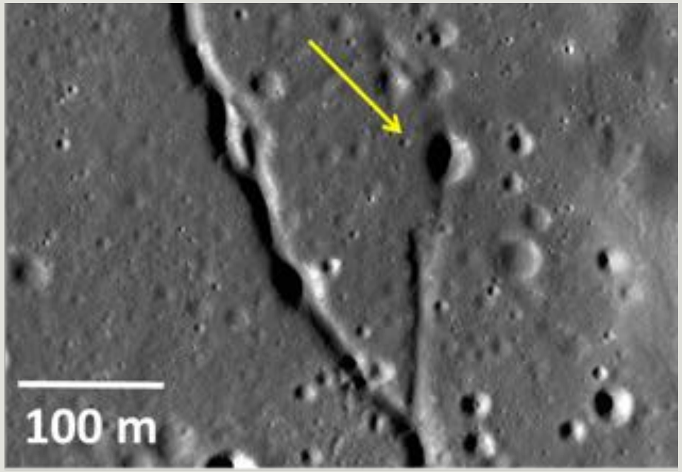
Rima Bode Regional Pyroclastic Deposit (~6600 km^2)
Lunar Orbiter IV 109, ~120 km across



Ap 17 glass & crystalline beads (G. Ryder)

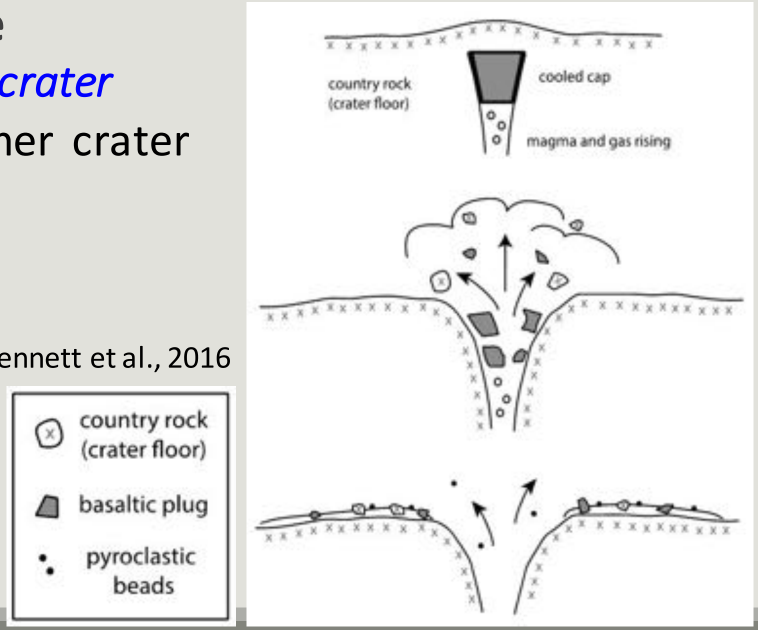
Localized Pyroclastic Deposits

- **Formed by Vulcanian-style eruption**
  - Intermittent, violent explosion caused by degassing near surface, disruption of a plug as magma rises in a dike (*Head & Wilson, 1979*)
  - **Volatile:** CO-rich gas produced by graphite oxidation (*Fogel & Rutherford, 1995*)
  - ***Mixed juvenile and non-juvenile materials***
    - ***Glass, crystalline basaltic (Hi FeO), fragmented country rock***
- **Type Example**
  - *Alphonsus crater*
  - Oppenheimer crater



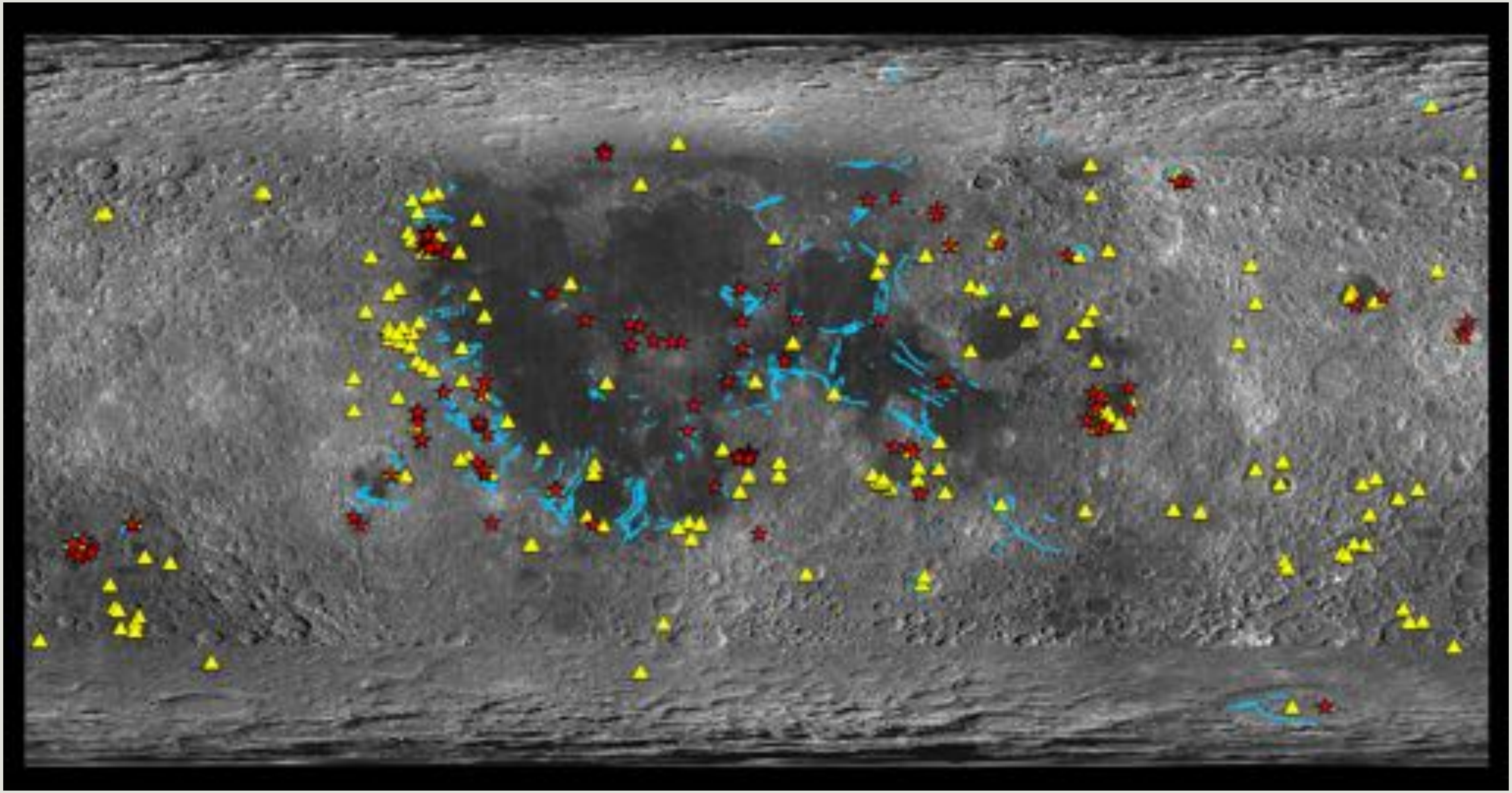
Alphonsus crater, Floor Vent #6
Kaguya Terrain Camera

Bennett et al., 2016



Globally Distributed

USGS



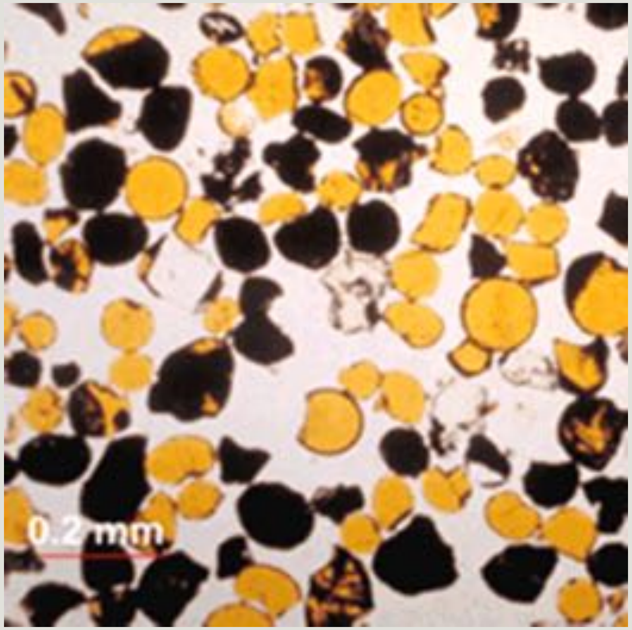
Pyroclastic deposits (Gaddis et al., 2003; Gustafson et al., 2012)
Floor-fractured craters (Jozwiak et al., 2015)
Fractures/faults (Wilhelms, 1987)

Resource Potential

USGS

Comprised of 'primitive' glass and quenched spheres

- Relatively unprocessed materials from deep within the lunar mantle (~300 to 400 km depths)
  - High Mg/Al, MgO, mg#; lower Al_2O_3 and CaO than mare basalts
- Interior crystals of olivine, spinel, ilmenite needles, etc.
- Uniform grain size, ~40 microns
- Surficial geochemical enrichments in >25 volatile elements
  - e.g., Au, Ag, Cu, Cd, F, S, Z (McCubbin et al., 2015)
- Contain **FeO**: **16 to 24 wt %**
- Variable amounts of **TiO_2**, related to color
  - **Green: <1 to 5 wt%**
  - **Yellow: 5 to 9 wt %**
  - **Orange: 9 to 14 wt %**
  - **Red-black: >14 wt%**
- 25 varieties of volcanic glass described by Delano (1986), several others identified since



Ap 17 spheres viewed through a microscope. These have ~8 wt% TiO2. (G. Ryder)

Resource Potential #2

Indigenous Magmatic Water

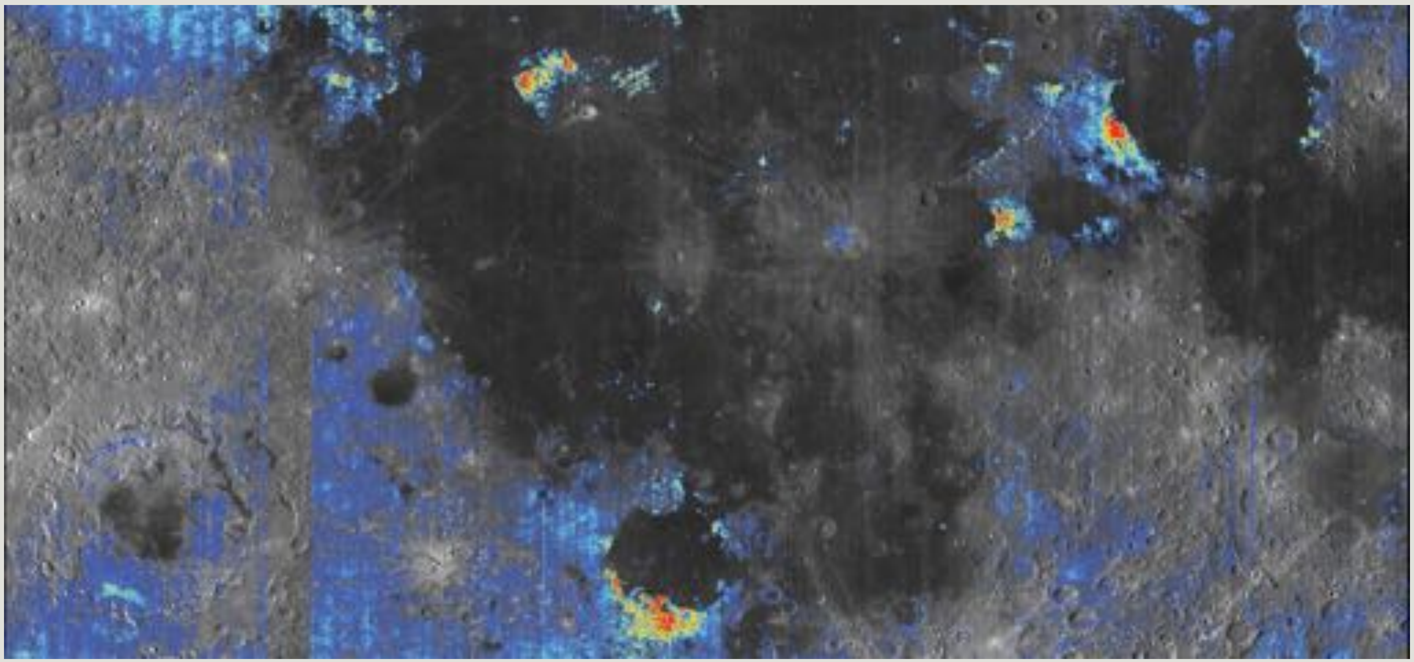
- The Moon is generally volatile-depleted
- BUT, recent sample analyses of melt inclusions in glass samples from Ap15, Ap17 found evidence for water and other magmatic volatile species
  - ~30 to 36 ppm of magmatic water in Ap 15 glass beads (Saal et al., 2008)
  - Correlations with other magmatic elements (Chlorine, Fluoride, Sulfur)
  - Concentration of volatiles decreased toward edges, indicating they were not contaminants from Earth
  - 270-1200 ppm H_2O in olivine crystals from Ap17 (Hauri et al., 2011)
    - From a primary lunar magma
    - Source water abundances of 80-440 ppm, comparable to MORBs
  - Summarized by McCubbin et al., 2015; Hauri e al., 2017

Apollo 15 green glass beads about 0.1 mm across (Ap 15 S79-32188)

Resource Potential #3

Mapping of Lunar Water

- Use of Moon Mineralogy Mapper (M3) data, quantitative analysis of strength of the 2.85-micron band (ESPAT), mapping of OH- and/or H_2O-bearing minerals
- Water abundances up to 150 ppm at large pyroclastic deposits, 300 to 400 ppm near vents



ESPAT=effective single particle absorption thickness

Milliken & Li, 2017

Resource Potential #4

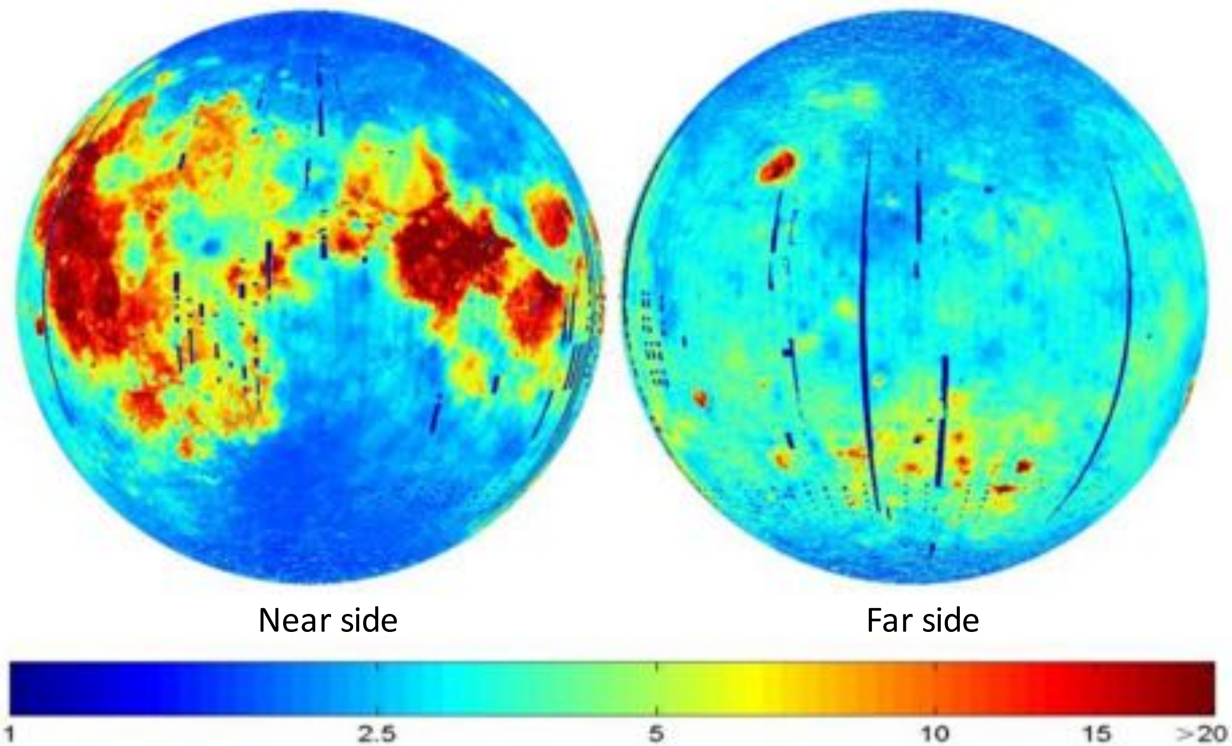
Exogenous Volatiles

- Solar-wind implanted volatiles (e.g., H, ^{3}He) in mature, Hi-Ti lunar regolith
- Evenly distributed in top 2-3 m, requires heating (300°-900° C) to release (Fegley & Swindle, 1993)

Table 1. Average concentrations of solar wind implanted volatiles in the lunar regolith (Fegley and Swindle 1993), where the quoted errors reflect the range (± one standard deviation) of values found at different sampling locations. The corresponding average masses contained within 1 m^3 of regolith (assuming a bulk density of 1660 kg m^{-3}; Carrier et al., 1991) are also given.

Volatile	Concentration ppm (μg/g)	Average mass per m^3 of regolith (g)
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

Crawford, 2015

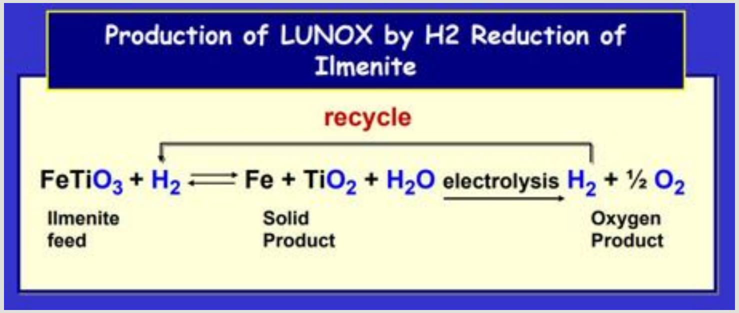


Estimated concentration of ^{3}He (ppb by mass) in the lunar regolith

Fa & Jin, 2007

In-Situ Resource Utilization

- Use of in-situ lunar resources can reduce costs of surface operations
  - H_2O ~ oxygen, drinking water for life support
  - H ~ rocket fuel, reducing agent
  - C, N, S could support lunar agriculture
- Pyroclastic deposits are rich in FeO & TiO_2
  - Extraction of oxygen (>20 methods to choose from; Taylor & Carrier, 1992)
  - Reduction of ilmenite is popular; requires H, energy
- Survey mode requires mobility, accessibility, traversability
  - Supports horizontal assessment of feedstock, estimates of thickness and vertical distribution from vent outward, determination of consistency of materials
- Sample return provides more precise determinations of composition, calibration for remote mapping
  - Ilmenite content
  - Presence of olivine
  - Indigenous water
  - Surface-correlated and solar-wind-implanted volatiles

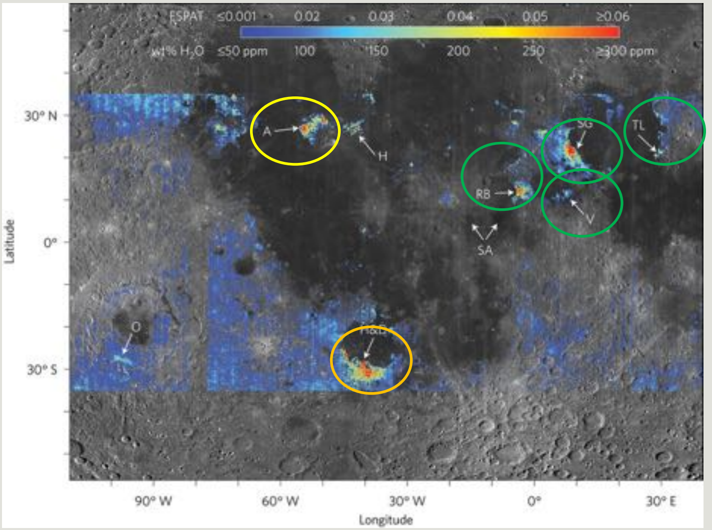


From Larry Taylor

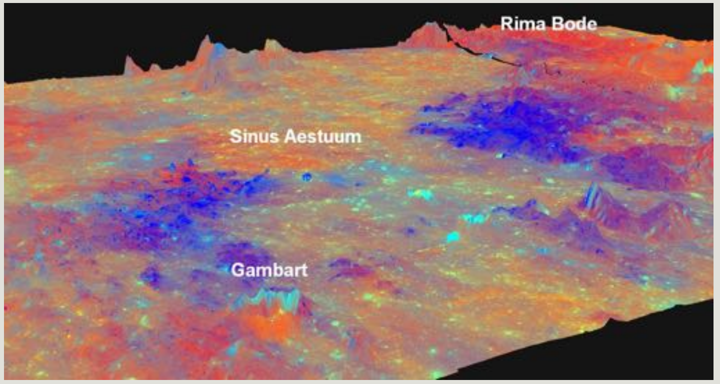
3-D Printed Moon Base (ESA)

Lunar Landing Sites

- SKGs to be addressed at lunar pyroclastic deposits
  - Understanding planetary volcanic processes
  - Understanding the Moon's resource potential
  - Understanding the nature & distribution of lunar volatiles
- Science questions (examples)
  - How old are the lunar pyroclastic deposits?
  - Are some eruption styles more likely to be associated with deposits with indigenous water?
  - Which deposits contain olivine that can be tied to deep lunar interior origin?
  - How thick/uniform are the deposits? Does thickness vary? How much material is present?
- What sites?
  - "Black spot" locations, high iron, titanium, H, H_2O, surface-correlated volatiles, water
    - Taurus-Littrow, Sulpicius Gallus, Rima Bode, Vaporum, etc.
  - Humorum
  - Aristarchus plateau (Jawin et al., this session)



ESPAT (Milliken & Li, 2017)

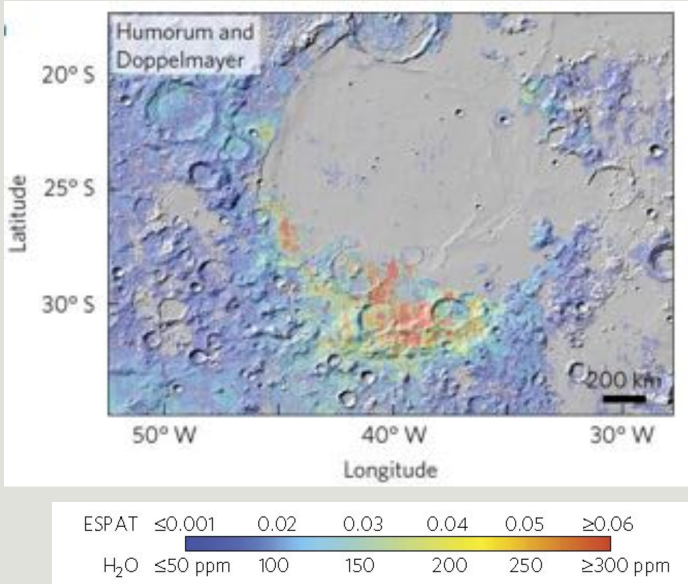


3D Sinus Aestuum, Rima Bode (Kaguya MI draped on SLDEM15)

Thanks for listening!

Lunar Landing Sites

- Example Landing Site: Humorum
  - Regional extent (1500 km^2), smooth-surfaced, Hi-FeO
  - Precursor remote characterization
    - High spatial resolution (<100 mpp), hyperspectral imager to map ~3 micron absorption band
      - Characterize abundance, distribution of mafic minerals and indigenous water in detail
    - Use LROC data (~1 mpp) for deposit thickness estimates, boulder& crater hazards
    - Use LOLA data to develop slope maps
  - Rover mission (ground contact at multiple sites)
    - Alpha Particle X-ray Spectrometer: Bulk chemistry
    - Neutron Spectrometer: Measure bulk hydrogen, water content at multiple sites
    - Pancam color imager:
      - Multispectral mapping (composition) survey
      - Observe any change(s) with time
  - Sample return
    - Multiple samples of mature soil, quenched glass, crystallized beads
    - Analysis of magmatic water (abundance, distribution, etc.)
    - Ground-truth for remote measurements
    - Feedstock assessment and viability for in-situ extraction



Milliken & Li, 2017